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SASOL: South Africa's Oil from Coal Story: Background for Environmental Assessment

TRW Environmental Engineering Div, Redondo Beach, CA

Prepared for

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Background for Environmental Assessment

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SASOL:
SOUTH AFRICA'S OIL FROM COAL STORY

- BACKGROUND FOR ENVIRONMENTAL ASSESSMENT

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ABSTRACT

The report describes the world's only oil-from-coal plant, known as SASOL, operated by South Africa since 1955. When almost $7 billion worth of expansion is completed in the early 1980's, three SASOL plants will produce a total of 112,000 barrels of oil per day, or about half of South Africa's needs. Production costs average $17 per barrel, well below the 1979 OPEC price of more than $20 per barrel.

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The U.S., like South Africa, has vast coal reserves. Although comparisons are difficult, it has been estimated that oil could not be produced from coal in the U.S. for less than $27 per barrel and perhaps as much as $45. The South African system is the only commercially proven process for the production of synthetic liquid fuels. The report provides some of the background on a process that will receive high priority for environmental assessment.

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1. Introduction

Since 1955, South Africa has operated the only oil-from-coal plant in the world. The plant is known as Sasol, an acronym for South African Coal, Oil, and Gas Corporation. When almost $7 billion of expansion is completed in the early 1980's, three Sasol plants will produce a total of 112,000 barrels of oil a day or about half of South Africa's needs. Production costs amount to $17 per barrel, well below the OPEC price of around $20 per barrel and much less than the $31 per barrel that South Africa has to pay on the spot market. South African motorists pay about $2.40 per gallon of gasoline (63¢/liter) at the pump.

Sasol converts coal to liquid fuels in two steps (Figure 1). First, the coal is burned with oxygen and steam under pressure to yield a gaseous mixture which is principally hydrogen, carbon monoxide, and methane. This gas is cleaned of impurities using processes that produce valuable chemical by-products. Once this is completed, the gas is passed over an iron-based catalyst in the second step to produce liquid fuels. Sasol produces a full range of hydrocarbons including fuel gas, liquefied petroleum gas (LPG), gasoline, diesel oil, parafin waxes, and chemicals such as alcohol and acetone. The yield of products obtained can be altered by changing such variables as the temperature, pressure, catalyst, or feed gas composition.

Even though Sasol's operation is helped by South Africa's abundance of cheap labor and low cost coal, Sasol's success indicates that producing synthetic fuels from coal is one solution to meeting the energy needs of a country without depending on natural gas or crude oil.

The United States, like South Africa, has vast coal reserves and decreasing reserves of natural gas and crude oil. The current world-wide energy crisis has revealed the vulnerability of the United States' oil and natural gas supplies to uncontrolled events in other parts of the world. Therefore coal must by necessity play an ever widening role in America's energy future. The abundance of oil and natural gas in the past has determined the energy forms Americans are accustomed to using.

CONVERTING COAL INTO SYNTHETIC FUELS

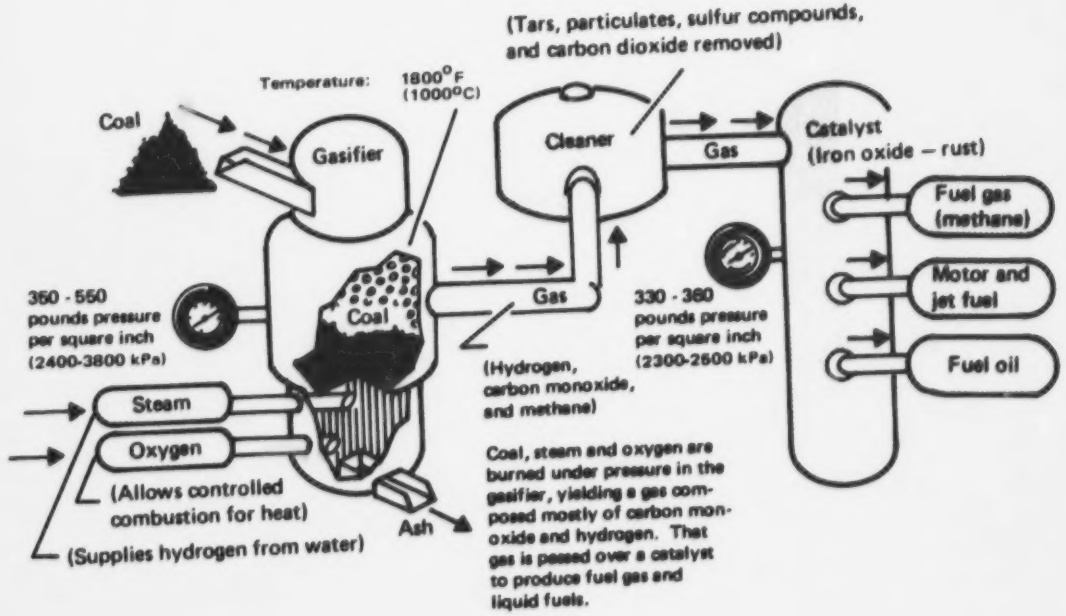
(Tars, particulates, sulfur compounds, and carbon dioxide removed)
Temperature: 1800°F (1000°C)
Coal
Gasifier
Cleaner
Gas
Catalyst (iron oxide – rust)
Fuel gas (methane)
Motor and jet fuel
Fuel oil
350 - 550 pounds pressure per square inch (2400-3800 kPa)
Coal
Gas
330 - 360 pounds pressure per square inch (2300-2600 kPa)
(Hydrogen, carbon monoxide, and methane)
Steam
Oxygen
(Allows controlled combustion for heat)
(Supplies hydrogen from water)
Ash
Coal, steam and oxygen are burned under pressure in the gasifier, yielding a gas composed mostly of carbon monoxide and hydrogen. That gas is passed over a catalyst to produce fuel gas and liquid fuels.

Figure 1. South Africa's Sasol Process

Coal is a solid fuel. If coal is to be more flexible for America's current market requirements, it must be converted to the gas and liquid energy forms that meet today's needs. For this reason, the South African Sasol process is of great interest to Americans.

2. Historical Background

South Africa has large deposits of low grade coal but no deposits of oil have ever been found. The country depends on coal for about 80% of its energy needs, more than any other modern industrial nation. The possibility of producing hydrocarbons from coal has always attracted the attention of its scientists. In 1927, a White Paper was published discussing the available processes for the production of oil from coal. Developments in Germany were closely followed, especially after the first announcements of the commercial feasibility of the Fischer-Tropsch process for the conversion of coal gas to liquid hydrocarbons were made in 1935. Between 1936 and 1939, nine plants, with a total rated annual output of 820,000 tons (740,000 metric tons, mt) of synthetic oil, were erected in Germany. The synthetic fuel industry developed by the Germans during the war was highly uneconomical but it provided gasoline for tanks, trucks, and planes. Of their final products, 46% was gasoline, 23% diesel oil, 3% lubricating oil, and 28% was refined waxes, detergents, and synthetic fat. After the war, the relative costs of coal and oil dictated the shutdown of the German synthetic fuel industry. Germany has done little in the field since.

The first large-scale German plant was still under construction in 1935 when a South African mining corporation, the Anglo Transvaal Consolidated Investment Company, better known as Anglo Vaal, acquired the South African rights to the Fischer-Tropsch process. Valuable pioneering work was done by Anglo Vaal in the 1930's. Preliminary tests were carried out on coal found in the eastern Transvaal district of South Africa, and during 1937 a complete specification for a suitable plant was drawn up. Tenders were invited but progress on the project was interrupted by the outbreak of World War II in 1939.

United States scientists and engineers had been frequent visitors to Germany during the 1930's. During that time the United States was working on its own variation to the Fischer-Tropsch process which used a moving powdered catalyst rather than the stationary pelletized catalyst developed

by the Germans. South African interests acquired rights to the American version of the Fischer-Tropsch process toward the end of the war.

In 1946 a new study was made and negotiations started with the South African government for an agreement on the fiscal structure within which an oil-from-coal plant could be established. In 1947, the Liquid Fuel and Oil Act was passed and a Liquid Fuel Advisory Board was established. It was evident that the new industry would be one of the biggest single enterprises ever established in South Africa and that its success would very much depend on such factors as government policies and taxation. The Advisory Board was instructed to examine all factors involved and to draw up a license which would give this new industry security for at least a number of years. This license was finalized in 1949.

By that time, Orange Free State gold mining expansion was in full swing and capital for less spectacular operations was scarce. At this stage, the sponsoring company approached the government for financial assistance. The great capital outlay required for the erection of a plant was beyond the means of Anglo Vaal. An Interim Commission appointed by the government to examine the proposed undertaking recommended that the process should be taken over from Anglo Vaal and that a government financed company should proceed with the venture.

The South African Coal, Oil, and Gas Corporation Ltd. (Sasol) was formed and incorporated under the Companies Act in September 1950 as an ordinary public company. It is not a government company in the normally accepted sense, but all its shares are held by the Industrial Development Corporation, a government company with its own charter. The government appoints the majority of directors, including the chairman, and the remaining directors are appointed by the Industrial Development Corporation. Sasol operates like a normal business concern, with an autonomous board of directors and is subject to South African company law and taxation.

The new company invited several internationally known engineering firms to submit suitable proposals with estimated costs for a complete installation. After examining the five offers received it became clear that important technical and economic advantages would result if the processes submitted by one German and one United States company were combined into an integrated project.

The ideal site for the oil-from-coal plant proved to be the northern corner of the Free State. Here a vast coal field exists close to the Vaal River and the concentrated market of the country's industrial center of the Witwatersrand. Sasol acquired 8000 acres (3000 hectare) of farmland for the erection of its factory complex and the establishment of the township of Sasolburg.

Shaft sinking at Sasol's coal mine and the planning of the plant and the township commenced in 1951. In 1955 reaction was accomplished for the first time in the synthesis reactors. By the end of the year the first motorists filled up their tanks with Sasol gasoline. Sasol's total capital investment was in the vicinity of $450 million.

3. Sasol I, Sasol II, Sasol III

The successful operation of the first Sasol plant (hereafter referred to as Sasol I) represented a major pioneering achievement in the area of coal technology. Sasol I is a vast complex which includes in addition to its oil-from-coal plant, a refinery and facilities for producing important industrial petrochemical feedstocks. The plant presently is the only fully integrated commercial synthetic fuels from coal plant in the world. Despite many technical difficulties that had to be overcome during the early years after startup, in most cases the actual output now exceeds the design figure. Sasol I converts five million tons (4.5 million mt) of coal per year to 160 million gallons (600 million liters) of gasoline plus vast quantities of liquid and gaseous fuels and petrochemicals. And contrary to early predictions, Sasol I has turned into a commercially profitable undertaking. Pretax profits in 1978 were $140 million on sales that totaled close to $1 billion. The oil produced by Sasol I is better quality than normal crude oil because the sulfur and other impurities have already been removed before the refining step. Gasoline from Sasol is indistinguishable in look and smell from gasoline refined from crude oil and no problems have been experienced in using liquid fuels from Sasol in blends for regular and premium gasoline and diesel oil. Gasoline from Sasol I accounts for about 7% of the market in South Africa.

The first step in the production of oil is the gasification of coal. Lurgi pressure gasifiers using steam and oxygen were selected because their operability had already been demonstrated and they had the advantage of being able to work on the low grade, high ash coal available to Sasol. The crude synthesis gas from the Lurgi gasifiers is fed to a gas purification unit where it is scrubbed with methanol to remove sulfur, carbon dioxide, tars, oil, phenols, ammonia, cyanides, and other unwanted components. The purified synthesis gas then undergoes the Fischer-Tropsch synthesis process, the combination of hydrogen and carbon monoxide with the aid of an iron catalyst to produce a range of hydrocarbons including motor fuels.

Two Fischer-Tropsch synthesis processes are used at Sasol I: the German developed process in which the pelletized catalyst is packed into a fixed bed reactor, and the American concept in which the powdered catalyst is swept along by the gas stream in a circulating fluid bed reactor system. The first process produces mainly higher boiling point materials consisting of waxes, some oils with medium boiling point such as diesel oils, and smaller amounts of gasoline, liquefied petroleum gas and chemicals. In contrast, the second process produces mainly low boiling point materials such as liquefied petroleum gas and gasoline as well as a considerable amount of chemicals such as alcohol and acetone. The unique combination of the two processes yields virtually the full range of products normally derived from crude oil in addition to a number of others usually manufactured in petrochemical plants. Sasol I is also the major supplier of industrial gas via a high-pressure pipeline to South Africa's industrial areas.

Sasol I has become the hub of South Africa's chemical industry, a group of about 30 plants producing a large range of petrochemical products: fertilizers, plastics, synthetic rubber, detergents, chemicals. In order to meet the ever growing demand for its products, Sasol I has successfully initiated and completed improvement and expansion programs over the years to supply important feedstocks (butadiene, styrene, ammonia, ethylene) to the chemical industry. In addition, in 1975 Sasol I implemented a $65 million expansion program which increased the capacity of the gasification plant by 40% and which doubled the supply of industrial gas.

As a result of rising crude oil prices since the Yom Kippur War (1974) and the Arab oil boycott, the South African government in a major move away from dependence on imported crude oil announced in December 1974 that it would build a second oil-from-coal complex, Sasol II. In addition, the move will save considerable sums in foreign exchange which South Africa uses to pay for imported oil. Sasol II will be three times the design capacity of Sasol I, or in terms of petroleum production, Sasol II will be the equivalent of a refinery capable of refining 2.9 million tons (2.6 million mt) per year of crude oil. The plant will consume 14 million tons (12.8 million mt) per year of coal as compared with five million tons (4.5 million mt) at Sasol I.

Sasol II is based on the same technology as Sasol I, that is, Lurgi gasifiers followed by the Fischer-Tropsch synthesis. Sasol I uses both the fixed bed and circulating fluid bed synthesis processes to produce the full range of light to heavy hydrocarbons. However, the objective of Sasol II is to produce motor fuels (gasoline and diesel) for which the circulating fluid bed is more suited. In addition, the possibilities for scale up are limited for the fixed bed reactor. For these reasons, the Sasol II plant will use only circulating fluid bed synthesis reactors which were perfected at Sasol I.

Construction got under way in 1976 on a flat, treeless 1850 acre (750 hectare) site about 80 miles (130 km) east of Johannesburg. The work force reached 15,000 during peak construction and the plant is scheduled for completion early in 1980. In addition, a town called Secunda (Latin for second) is being built nearby. The Sasol II complex will produce enough gasoline to supply 30% of South Africa's motor fuel needs. Sasol II will cost $2.8 billion and is being financed by increased gasoline levies, by suppliers' credits, and by government-voted money. To put the cost in perspective, South Africa expected to spend $2.3 billion on imported oil in 1979.

Immediately after the downfall of the Shah of Iran in early 1979, South Africa announced the planned construction of Sasol III alongside Sasol II. The new Iranian revolutionary government had decided to cut off oil supplies to South Africa. Iran had been South Africa's principal supplier. Sasol III will be almost an exact copy of Sasol II to save design costs, and may be ready for full production by 1984. Because of inflation, construction costs for Sasol III are estimated at $3.8 billion. Once the three plants are in operation, they will produce about 112,000 barrels of oil per day, approximately half of South Africa's needs in the 1980's.

4. Detailed Description of the Process

The Sasol I complex is made up of the following processing units:

- Coal mining and preparation
- Coal gasification
- Oxygen and steam production
- Gas purification
- Fischer-Tropsch synthesis
- Recovery and treatment of gaseous products
- Reforming of methane to synthesis gas
- Recovery and refining of liquid products

The Sasol II and Sasol III complexes with some modifications consist of the same processing units. The units that make up a Sasol plant along with the reasons for their selection are described in this section. Differences between the three Sasol plants will be pointed out. A block diagram of the Sasol I process is shown in Figure 2.

4.1 Sasol I

Sasol I is located 50 miles (80 km) south of Johannesburg on top of a vast coal field close to the banks of the Vaal River which is South Africa's major source of water. Sasol I is supplied with coal from its own nearby mine, Sigma Colliery. Production amounts to five million tons (4.5 million mt) per year. Sigma produces a non-caking, low-grade coal with an ash content of 30 to 35%, a sulfur content of 0.5%, and a heating value of 8380 Btu's per pound (19,480 kJ/kg) on a dry basis. A typical analysis is shown in Table 1. The coal is present in three seams, having mineable heights of 8 to 10 feet (2.5 to 3 m) each. The seams are separated by layers of shale, mudstone, and sandstone of varying thickness. The mine is under 100 to 200 feet (30 to 60 m) of white sandstone.

The mining technique used is the mechanized room-and-pillar. The coal recovery efficiency is approximately 52%. Mined coal is transported via conveyor to primary crushers situated at the bottom of the inclined coal hauling shafts. The coal is lifted to the surface by conveyor and discharged into storage bunkers of 12,000 ton (11,000 mt) total capacity.

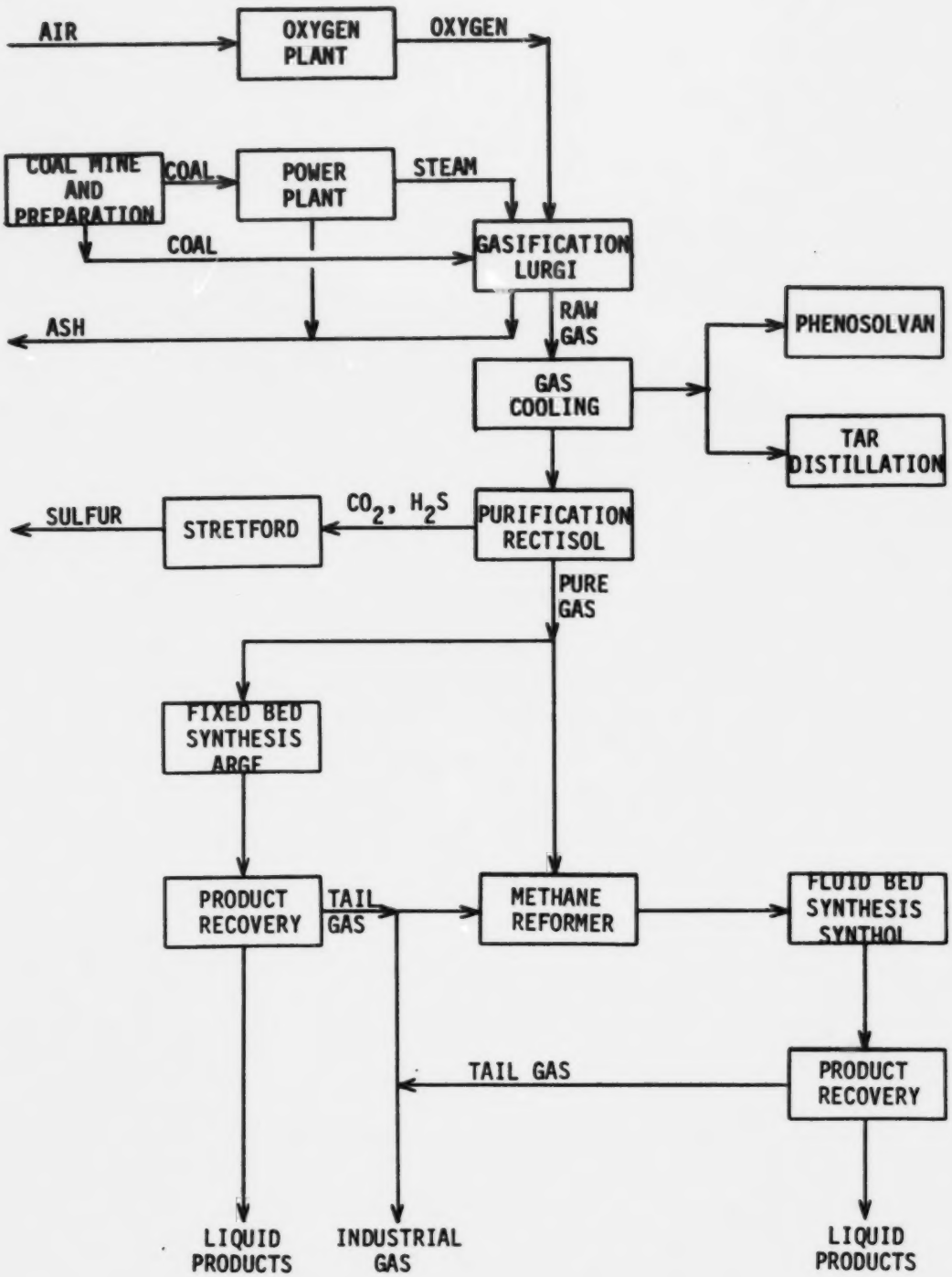

Figure 2. Block Diagram of Sasol I Process

Table 1. Typical Analysis of Sasol Coal

	Sasol I	Sasol II
Dry Basis		
Ash	35.9 %	27 %
Volatiles	22.3	25
Fixed Carbon	41.8	48
Ultimate Analysis as Received		
Carbon	45.4 %	54.2 %
Sulfur	0.4	1.1
Nitrogen	1.1	1.3
Hydrogen	2.5	2.9
Oxygen	7.9	9.4
Ash	32.0	25.6
Moisture	10.7	5.5
Total	100.0 %	100.0 %
Ash Properties		
Softening Point	2440°F (1340°C)	2350°F (1290°C)
Melting Point	2600°F (1430°C)	2430°F (1330°C)
Fluid Point	2690°F (1475°C)	2480°F (1360°C)
Gross Heating Value (dry)	8,380 Btu/lb (19,480 kJ/kg)	10,300 Btu/lb (23,940 kJ/kg)

Surface conveyor belts transport the coal from the storage bunkers to the secondary crushers and screens. The final product consists of two coal sizes, less than 0.4 inch (1 cm) and between 0.4 and 2 inches (1 and 5 cm), which are transferred separately on twin conveyors to the 60,000 ton (54,000 mt) Sasol factory storage bunkers. Coal is kept damp on the conveyor belts by water sprays at suitable points to prevent dust formation. The less than 0.4 inch (1 cm) fraction (approximately 50% of the total) is used in the power plant to produce electric power and heat for steam production, whereas, the 0.4 to 2 inch (1 to 5 cm) fraction is fed to the Lurgi gasifiers.

The Lurgi pressure gasifiers are fixed-bed, water-cooled reactors that gasify the coal in the presence of oxygen and steam to yield a synthesis gas containing methane, carbon monoxide, hydrogen, carbon dioxide, ammonia, hydrogen sulfide, steam, and numerous other compounds. Lurgi pressure gasifiers were selected because they had already been demonstrated in smaller sized installations and had the advantage of being able to work on the rather low grade, high ash coal available to Sasol I. The fact that they operated at a pressure of approximately 350 psi (2400 kPa) which was also the desired operating pressure for the Fischer-Tropsch plant was an additional advantage.

Thirteen Lurgi gasifiers consume coal at a total rate of approximately 8,000 tons (7300 mt) per day. These gasifiers are 12 feet (3.7 m) in diameter and are the largest of their kind in commercial operation. On an annual basis, 10.8 out of 13 gasifiers are in service. At this level, gas production is actually limited not by gasification but rather by gas purification capacities. The Lurgi gasifiers operate on the principle of countercurrent flow of coal to steam and oxygen which offers the best conditions for heat and mass transfer and optimum efficiency. The overall thermal efficiency of the gasifier system is approximately 75.5%. Gasification occurs at 1800°F (1000°C).

Consumption of oxygen and steam in the Lurgi gasifiers is a function of a number of variables, but typical Sasol values are 220 standard (0°C, 1 atm) cubic feet (SCF) of oxygen (6.2 Nm^3) and 62 pounds (28 kg) of steam per 1000 SCF (28 Nm^3) of raw synthesis gas produced. Raw gas production

averages 330 million SCF (9.3 million Nm^3) per day. Oxygen is produced in one of the world's largest air separation plants. About 13,000 tons (12,000 mt) of air are compressed and cooled down to -310°F (-190°C) every day in order to separate the oxygen and nitrogen and recover them in liquid form. The oxygen is used in the Lurgi gasifiers as well as in the partial oxidation methane reforming plant. The nitrogen is used in an ammonia plant.

Steam and electricity are generated in a power plant which consumes approximately 7,000 tons (6400 mt) of coal per day or 50% of the coal supplied to the Sasol I plant. Conventional pulverized fuel boilers are used. The steam generated is used not only for the gasification of coal, but also in the various plants inside and outside the Sasol complex.

Sasol I coal contains 30 to 35% ash which must be disposed of. The residual carbon is completely burned out of the ash with oxygen in the combustion zone at the bottom of the Lurgi gasifiers. This exothermic reaction helps supply the heat for the endothermic gasification reaction in the upper part of the gasifiers. The residue is essentially burned-out ash which is transported from the gasification and power plant areas by water in a low velocity sluiceway to the ash dewatering unit. Coarse ash is removed by conveyor belts to an ash dump. The fine ash is concentrated in a thickener and the concentrated fine ash is then dewatered in a slimes dam. The ash contains soluble inorganic salts that will leach out. The ash system is however an evaporative system for water and requires water make-up and no purge. Water drainage from the slimes dam is collected and pumped back into the ash sluiceway system. To prevent water seepage, the slimes dam was given an impervious clay layer from clay available on site. The slimes dam was built with an extensive drainage system to recover all seepage for return to the ash sluiceway system. Coarse ash contains no excess water and at least the outside of the dump soon dries out to such an extent that it will absorb rain water. No evidence of seepage from the ash dump has been found and no measures are taken against seepage. Success has been achieved in growing grass on the dumps to make them aesthetically acceptable. Regular samples of water from boreholes in the vicinity of Sasolburg have been taken over the years and no evidence of underground water pollution has been found.

Raw synthesis gas leaving the top of the gasifiers contains apart from carbon monoxide and hydrogen appreciable quantities of methane, carbon dioxide, hydrogen sulfide, and undecomposed steam. In addition, the gas contains cyanide compounds, tars, oils, phenols, organic sulfur compounds, and numerous other impurities in minor quantities. The iron-containing Fischer-Tropsch catalyst is very sensitive to sulfur, cyanide, and other compounds. Efficient purification of the synthesis gas is an essential requirement for high Fischer-Tropsch conversion rates. In addition, the raw gas contains about 30% carbon dioxide which must be brought down to a lower level.

After separation of entrained coal dust, the raw synthesis gas is cooled in a sequence of waste heat boilers and condensers. The raw gas contains large quantities of undecomposed gasification steam. During gas cooling this steam is condensed and the resulting aqueous liquor contains the water-soluble components that were in the gas, chiefly phenols and ammonia. The tars and oils are also separated from the synthesis gas during cooling. The oil and aqueous liquor streams are fed to tar distillation and Phenosolvan plants respectively. In the tar distillation plant, road primer, creosotes, and lighter naphthas fractions are separated. The naphthas are hydrogenated and distilled to produce benzoles for solvent use and for blending into gasoline. In the Phenosolvan plant, the aqueous liquor is treated by solvent extraction with an oxygen-containing organic solvent, butyl acetate, to remove the phenol compounds. The ammonia is then recovered by stripping with steam and converted to ammonium sulfate for fertilizer manufacture. There are 5.5 U.S. gallons of tar and oil and 17 pounds of ammonia recovered per short ton of coal gasified (23 liters and 8.5 kg per mt).

Stripped liquor, containing approximately 240 and 250 parts per million (ppm) of ammonia and phenol, is processed in a conventional biological treatment plant together with effluents from other chemical plants in the area, as well as domestic sewage from the town of Sasolburg. Treated liquor is used in the factory for removal and transport of ash from the gasifiers. Ash acts as an adsorbent, reducing the residual oil content of treated liquor to less than 2.5 ppm.

Cooled synthesis gas leaving the waste heat boilers and condensers still contain impurities, including carbon dioxide, hydrogen sulfide, and an array of gum-forming compounds. These impurities are removed by methanol in the Rectisol plant. The Rectisol process is based on the capability of one solvent, cold methanol, to absorb all impurities present in gases from coal gasification in a single process step. Since the absorption capacity of methanol increases with decreasing temperature, the raw gas is contacted and scrubbed with liquid methanol at -67°F (-55°C).

At Sasol I, the Rectisol process (a total of four parallel streams) has a long term on stream record of 97%, and produces a purified gas containing 1.5% carbon dioxide and 0.07 ppm hydrogen sulfide. A typical composition of raw and pure synthesis gas is shown in Table 2. The extremely pure gas from the Rectisol process is suitable for the sensitive Fischer-Tropsch synthesis catalyst. The main energy consumption in the Rectisol unit is that used to drive the methanol circulation pumps and the refrigeration compressors. Approximately 0.9 KWH and 4.6 pounds (2 kg) of steam per 1000 SCF (28 Nm^3) of purified gas leaving the Rectisol process are required.

The off-gas (containing carbon dioxide and hydrogen sulfide) from the Rectisol plant is used as an expansion gas. Before this gas is vented to the atmosphere, hydrogen sulfide is removed and recovered as elemental sulfur in a Stretford sulfur recovery unit. The Stretford unit was installed in 1976. The limit set for gaseous effluents from the Stretford units both at Sasol I and Sasol II is 50 ppm hydrogen sulfide. Some hydrocarbons and other impurities are still present in the vent gas.

The purified gas emerging from the Rectisol plant undergoes the Fischer-Tropsch synthesis which produces hydrocarbons by the catalytic conversion of carbon dioxide and hydrogen according to the following equation:

$$n(CO + 2H_2) \longrightarrow (-CH_2-)n + nH_2O$$

Table 2. Typical Composition of Raw and Pure Synthesis Gas (Volume %)

Component	Raw Gas	Pure Gas
CO_2	31.4	1.2
H_2	40.2	54.0
CO	17.1	30.5
CH_4	10.2	13.6
H_2S	0.3	-
N_2+Ar	0.4	0.6
C_nH_m	0.4	0.1

Two types of Fischer-Tropsch reactors are used, the German developed fixed bed process (Arge) and the American fluid bed system (Synthol). The purified gas from the Rectisol plant is divided into two streams. The larger stream is fed directly to the fixed bed Arge synthesis units where a stationary pelletized catalyst is used. The gas conversion is not complete. The tail gas from the Arge units contains low-boiling hydrocarbons and carbon dioxide. These are removed in a Rectisol wash unit at subzero temperatures. The washed gas together with the remainder of the fresh gas from the purification plant enters a reforming plant where methane is reacted with steam and oxygen over a nickel catalyst to produce additional carbon monoxide and hydrogen. After adjustment of the hydrogen-carbon monoxide ratio, the gas is fed to the fluid bed Synthol plant where a circulating powdered catalyst is used. The tail gas of this plant is also recycled to the reforming units after removal of carbon dioxide. For both the Arge and Synthol plants there are recovery and refining plants downstream.

The fixed bed reactor produces in general straight-chain hydrocarbons with a high average molecular weight in the range of diesel oil and parafin waxes and a relatively low percentage of gasoline, liquefied petroleum gas, and oxygenated compounds (alcohols, ketones, organic acids). The fluid bed process produces branched olefins of a lower average molecular weight in the range of liquefied petroleum gas and gasoline, little high-boiling material, and some oxygenated products (Table 3). Although the basic chemistry for both reactors is the same, the different temperatures, method of catalyst contacting, recycle ratios, feed gas compositions, and hydrogen partial pressures employed in the two systems result not only in a difference in product selectivity, but also in a difference in the properties of hydrocarbons within the same boiling range. In general, the higher the reaction temperature the higher the content of olefins and the lower the average molecular weight of the products.

Table 3. Comparison of Fixed Bed and Fluid Bed Conditions and Products

	Fixed Bed	Fluid Bed
Conditions		
Temperature	430-490°F (220-255°C)	625°F (330°C)
Pressure	360 psig (2500 kPa)	330 psig (2300 kPa)
$CO + H_2$ Conversion, %	65	85
H_2/CO Ratio in Feed	1.7	2.8
Product Composition, Vol %		
Liquefied Petroleum Gas (C_3-C_4)	5.6	7.7
Petroleum (C_5-C_{11})	33.4	72.3
Middle Oils (diesel, furnace)	16.6	3.4
Waxy Oil	10.3	3.0
Medium Wax, mp 135-140°F (59°C)	11.8	-
Hard Wax, mp 203-206°F (96°C)	18.0	-
Alcohols and Ketones	4.3	12.6
Organic Acids	trace	1.0

Product Selectivity, Vol %	C_5-C_{12}	C_{13}-C_{18}	C_5-C_{10}	C_{11}-C_{14}
Paraffins	53	65	13	15
Olefins	40	28	70	60
Aromatics	0	0	5	15
Alcohols	6	6	6	5
Carbonyls	1	1	6	5

The fixed bed Arge system (a joint development of Ruhrchemie and Lurgi of Germany) consists of five reactors in parallel, each with a shell of approximately 10 feet (3 m) in diameter and a height of 42 feet (13 m). Inside each shell there are 2,000 vertical tubes, 2 inches (5 cm) in diameter, containing the pelletized iron catalyst. The tubes are surrounded on the shell side by a steam jacket. The gas is passed over the catalyst from top to bottom and the heat released by the exothermic reaction is absorbed by boiling the water in the shell. The reaction temperature is controlled by controlling the pressure of the boiling water. The Fischer-Tropsch reactions are highly exothermic, and one of the major design problems for both the Arge and Synthol systems is adequate heat removal from the reactor. About 7,500 Btu's of heat are released per pound of product (17,400 kJ/kg).

Figure 3 is a schematic drawing of the fixed bed Arge reactor. The reactor operates at 360 psig (2500 kPa). The life of the iron catalyst is six months during which time the operating temperature is increased from the starting point of 430°F (220°C) to a maximum of 490°F (255°C). The specific catalyst employed contains a number of promoters (including copper and potassium) and has to be partially reduced before it can be used. It is manufactured at Sasol.

The fixed bed synthesis accounts for about one-third of Sasol I's plant output. It came on line in 1955 with only minor problems and behaved more or less as designed. Production up to 140% of the design capacity has been achieved. The major disadvantage of the Arge reactor system is its limited scale-up potential. New, large synthetic fuel plants would require an impractical number of such reactors.

The synthesis products exit at the bottom of the Arge reactor. The tail gas is separated from the heaviest hydrocarbons which are obtained as reactor condensate. The hot gas then exchanges heat with the incoming feed gas and is further cooled and washed with sodium hydroxide solution in water-cooled condensers. The heat exchangers and the condensors produce hydrocarbon and aqueous condensates which are, after pressure release and recovery of the dissolved gas, sent to the refinery.

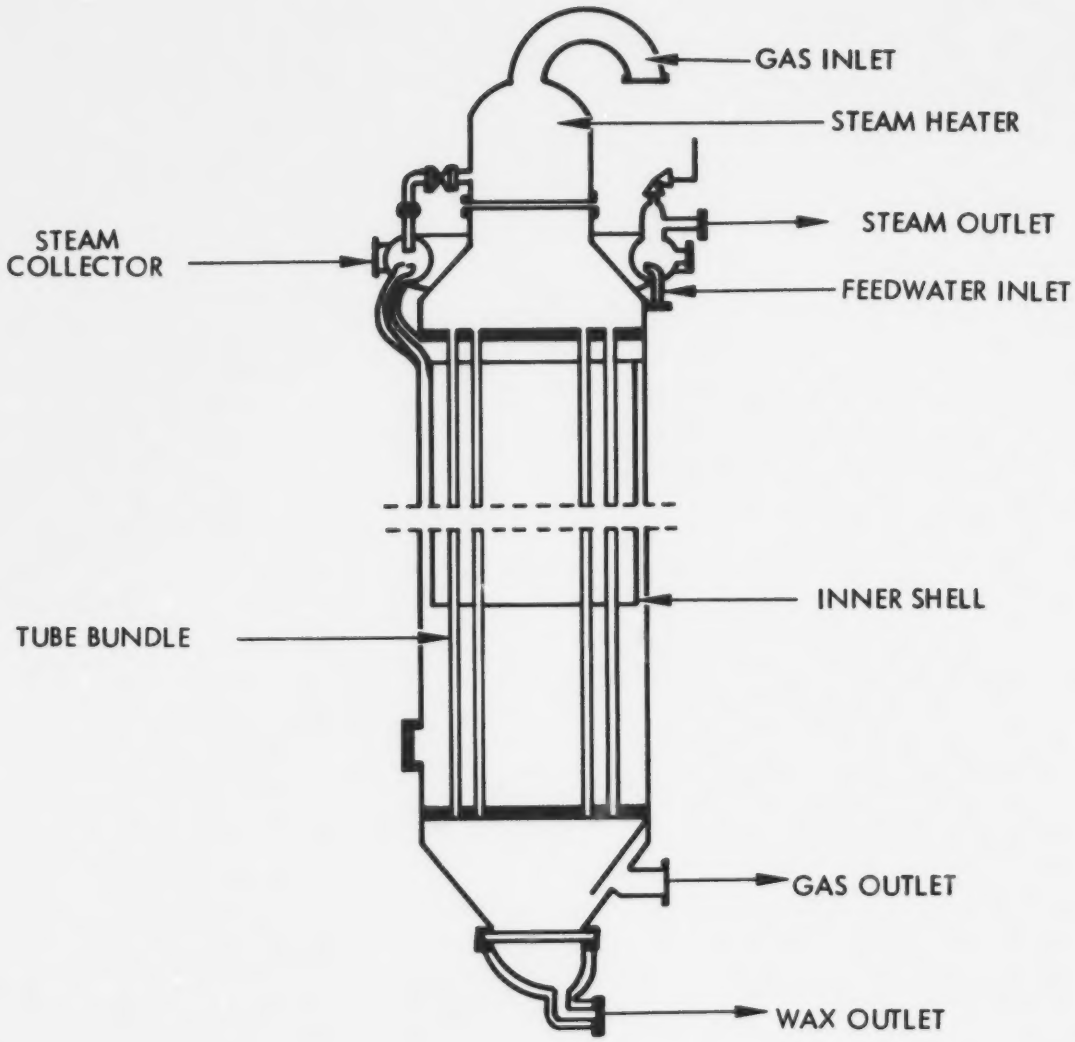

Figure 3. Fixed Bed Arge Reactor

The tail gas leaving the condensors is used for recycle, sold as industrial gas, or is sent to a methane reformer. The tail gas contains low-boiling hydrocarbons up to pentane, inclusively, and carbon dioxide. The hydrocarbons are removed in a Rectisol wash unit by heptane at -30°F (-35°C), followed by a methanol wash at -40°F (-40°C) to prevent a buildup of carbon dioxide. The washed gas together with fresh gas from the purification plant and tail gas from the fluid bed Synthol reactors is sent to a reforming plant where methane is reacted with steam and oxygen over a nickel catalyst at a temperature of about 1800°F (1000°C) to produce additional carbon monoxide and hydrogen. The Lurgi gasifiers and both Fischer-Tropsch synthesis processes produce methane as the lowest hydrocarbon and there is a tendency for methane to build up in the recycle streams. To make full use of the synthesis gas, it is necessary to reform methane back to hydrogen and carbon monoxide. Another complication is the presence of nitrogen and argon in the synthesis gas, most of which is introduced into the gas stream with the 98% oxygen from the air separation plant. The nitrogen and argon act as inerts in the system and have to be removed as a purge gas to keep them within an acceptable level.

The gas from the reforming plant is fed to the fluid bed Synthol plant. The Synthol process was developed by M.W. Kellogg of the United States. Each Synthol reactor consists of a feed system, a reactor tube, product-catalyst separation equipment, and a catalyst recycle hopper (Figure 4). Fresh feed and recycle gas at 320°F (160°C) are blended with finely divided, hot 625°F (330°C) iron catalyst at the base of the reactor. This gas-solid mixture comes rapidly to thermal equilibrium and rises up the Synthol reactor where exothermic Fischer-Tropsch and water-gas shift reactions take place. A significant fraction of the heat liberated is removed in waste heat boilers built into the reactor. In addition, the products and tail gas leaving the system at 625°F (330°C) remove a large amount of heat. The products are disengaged from the catalyst initially by gravity and subsequently by cyclone separation. The gas leaves the reactor and the recovered catalyst is collected in a settling hopper from which it is recycled through a stand pipe and slide valves to the feed gas inlet at the base of the reactor.

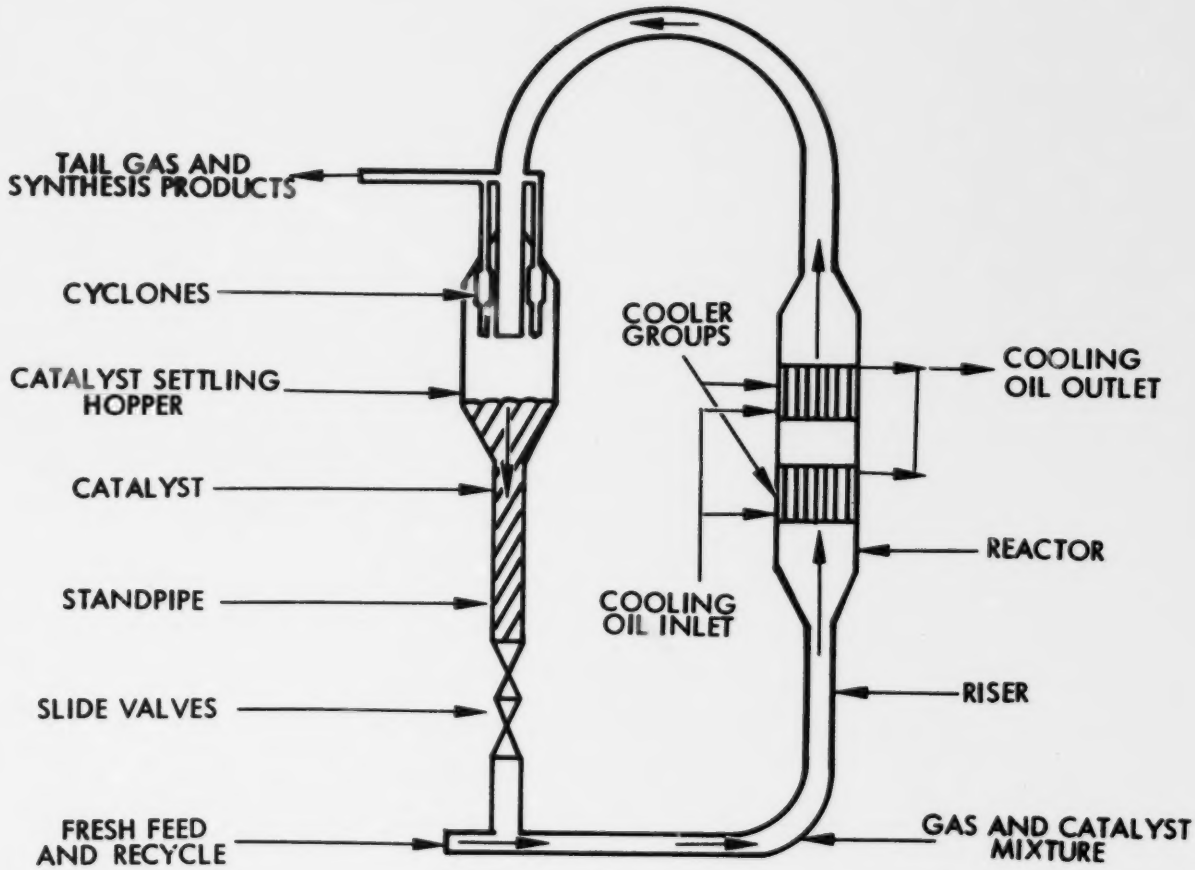

Figure 4. Fluid Bed Synthol Reactor

Three parallel Synthol reactors are in operation at Sasol I. Each has an inside diameter of seven feet (2 m), and a height of 120 feet (37 m). The reactors operate at 330 psig (2300 kPa) and 600 to 625°F (315 to 330°C). An ammonia synthesis type iron catalyst containing various structual promotors such as alumina and magnesium oxide is circulated through each reactor at a rate of 6,000 to 8,000 tons (5500 to 7000 mt) per hour. The reduced iron catalyst is gradually converted during synthesis into a mixture of free iron, iron carbides, and magnetite. The catalyst used in the fluid bed reactors was developed by Sasol.

At the time the Synthol plant was designed only pilot plant data were available. However, when the fluid bed plant was built, it behaved quite differently from what was predicted. Much additional experimentation, research, and modifications were needed at Sasol before the fluid bed system was developed to the point where it could be considered completely reliable. In contrast to the Arge reactor system, the Synthol reactors have distinct scale-up capability and are, therefore, practical for use in the large-scale synthesis of hydrocarbons. Fluid bed reactors will be used exclusively in Sasol II and III.

The products of the Synthol reactors and the tail gas are passed to a scrubber where the vapor is cooled from the reactor outlet temperature of 625°F to 300°F (330 to 150°C). The higher molecular weight hydrocarbons are condensed and separated. The heavy hydrocarbons are taken off the bottom of the scrubber and sent to the oil recovery plant. The vapor phase scrubber overhead is further cooled and sent to a separator where lighter hydrocarbons, aqueous chemicals, and the gas phase are separated. The light hydrocarbon layer is transferred to a countercurrent water-wash tower where any oxygenated products including alcohols, ketones, and organic acids are washed out. The washing water is added to the aqueous stream from the separator and sent to chemical recovery. A significant fraction of the non-condensible product gas from the separator is boosted to the reactor inlet pressure and recycled. The remaining tail gas is washed with an alkali solution and passed to an absorption system for recovery of light hydrocarbons. The absorber effluent gas is rich in methane and hydrogen. It is either used in ammonia synthesis, sold as industrial

gas, or reformed to carbon monoxide and hydrogen for recycle. When used in ammonia synthesis, hydrogen is separated from the Synthol tail gas by cooling to -315°F (-193°C). The hydrogen is then mixed with a correct amount of pure compressed nitrogen from the air separation plant and converted over an iron oxide catalyst to synthetic ammonia. The ammonia is converted to nitrogenous products for use in South Africa's agricultural industry. The methane fraction from the low temperature hydrogen separation unit is used as a blending gas to help control the heating value of the tail gas sold to industry. The clean fuel gas supplied to the nearby industrial areas of the Vaal Triangle and the Witwatersrand has a heating value of 500 Btu's per standard cubic foot (18,600 kJ/Nm^3). To meet the increasing demand for industrial gas, the coal gasification capacity of Sasol I was increased by 40% in the mid-1970's, doubling the supply of gas to industry. The expansion consisted of additional gasifiers, a Rectisol purification unit, additional oxygen capacity, and an aqueous liquor purification unit.

With the building of Sasol I, the South African petrochemical industry was firmly established. The solid hydrocarbons from the fixed bed process find many applications. The primary gasoline produced is a suitable motor fuel and the diesel oil is of an excellent quality. The liquid olefins provide raw materials for biologically soft detergents, and a wide range of high-viscosity, stable, lubricating oils. In addition, alcohols, ketones, aldehydes, organic acids, and esters are recovered from the aqueous streams that flow from the synthesis reactors. A partial list of Sasol products is presented in Table 4. The overall thermal efficiency of the Sasol process from coal as mined to saleable refined end products is 35 to 40%.

4.2 Sasol II and Sasol III

Early in 1980, South Africa's production of gaseous and liquid hydrocarbons from coal will triple with the startup of Sasol II, a $2.8 billion complex based on the same coal conversion and Fischer-Tropsch technology as Sasol I. Sasol I and II will produce enough gasoline to meet 30 to 40% of South Africa's needs.

Table 4. Sasol Products and Intermediates

Carbon Dioxide	Xylenol	Liquefied Petroleum Gas
Oxygen	Light Naptha	Industrial Gas
Nitrogen	Heavy Naptha	Acetone
Steam	Reactor Wax	Methyl Ethyl Ketone
Electricity	Soft Waxes	Higher Ketones
Ammonia	Medium Waxes	Methanol
Ammonium Nitrate	Hard Waxes	Ethanol
Ammonium Sulfate	Paraffin	Higher Alcohols
Phenol	Gasoline	Ethylene
Benzene	Diesel Oil	Butadiene
Toluene	Creosote	Styrene
Road Primer		Pitch
Fuel Oil		

Sasol II will concentrate on the manufacture of refined motor fuel rather than petrochemicals, although petrochemicals will be produced. The grass roots plant will produce 2.4 million tons (2.1 million mt) per year of saleable products, including 1.7 million tons (1.5 million mt) per year of gasoline and diesel oil. Sasol II is being financed by gasoline levies, suppliers' credits, and government-voted money. The rising cost of crude oil should make Sasol II economically very attractive when it comes on stream in 1980. This has been the case with Sasol I in recent years. Sasol production costs amount to $17 per barrel. This is well below the OPEC price of around $20 per barrel and much less than the $31 per barrel that South Africa has to pay on the spot market. Gasoline sells for about $2.40 a gallon (63¢/l) at the pump in South Africa.

In addition to research and development on improving the Fischer-Tropsch process, Sasol has closely followed the development of newer, more efficient methods of producing oil from coal such as coal liquefaction. Coal liquefaction produces liquid fuels from coal in essentially one step, as opposed to the two step (coal gasification followed by Fischer-Tropsch synthesis) process used at Sasol I. Although a coal liquefaction plant would have some advantages in thermal efficiency and capital investment, Sasol decided that the process had not been developed to the point where it could seriously be considered for large scale commercial application when the decision to build Sasol II was made in the wake of the 1974 Yom Kippur War. For this reason, Sasol II will be based on Fischer-Tropsch technology.

The Sasol II plant and a new grass roots town Secunda are located in a farming area of the Transvaal province, 80 miles (130 km) east of Johannesburg. The mine, whose shaft openings are just a quarter mile (0.4 km) from the Sasol II gates, contains sufficient coal to meet the plant's needs for about 60 years. There are other coal deposits nearby. Coal for Sasol II lies in three beds, one upon the other, and is between 300 and 600 feet (100-200 m) below the surface. The seams are each approximately 10 feet (3 m) thick. The coal will be mined by means of continuous mining, longwall, and room and pillar techniques. There will be no open pit mining. The coal will be continuously transported from the mine by belt conveyor.

The total amount of coal consumed by Sasol II will be approximately 14 million tons (12.8 million mt) per year of which 9.2 million tons (8.4 million mt) will be gasified and 4.8 million tons (4.4 million mt) used for steam and power production. The steam production will be between four and five million pounds (about 2 million kg) per hour and the power production will be 240 megawatts. Additional power will be bought from the public utility system which operates large power plants in the Sasol II area.

Coal for Sasol II is higher in carbon and lower in ash than Sasol I coal (Table 1). Since Sasol II coal is very friable, crushing and screening to the same size as for Sasol I would result in a higher proportion of fines than is desirable for gasification. Fines in coal fed to the gasifiers can be carried out with the raw synthesis gas and be not only a loss to the process but result in undersirable problems with the gasification by-products. Wet screening of Sasol II coal will permit a sharp separation of the fines. The fines will be used in the generation of steam and power for Sasol II. In fact, the amount of power production was chosen to arrive at a balance between fine and coarse coal.

The coarser coal is fed to the coal gasification plant. The choice as to which gasification system to use was between the Lurgi pressure gasifier with which Sasol is completely familiar and a high temperature, low pressure entrained gasifier system using pulverized coal. As a result of the high temperature, the latter system does not produce coal gasification by-products, nor does it produce methane, but its oxygen consumption is high and the raw gas needs compression to bring it to an acceptable level for purification. The Lurgi pressure gasification has the advantage for the Sasol objective that gas is produced approximately at the pressure required for the Fischer-Tropsch synthesis so that compression of large volumes of raw gas is not required. In a large plant such as Sasol II, processing facilities for the gasification by-products can be economically justified especially where the overall objective of the plant is to produce hydrocarbons. All these considerations expressed in terms of capital investment, operating cost and income indicated that

for Sasol II, Lurgi gasifiers will again be used. Over the years a number of improvements to the Lurgi gasifier have been made allowing the extrapolation to larger capacity within the limits of confidence. Sasol II will require 13,000 tons (12,000 mt) of oxygen per day from air separation plants.

For the gas purification section, a large number of options were available to remove not only the last traces of tar and tar products but also organic sulfur and hydrogen sulfide as well as carbon dioxide. Only the Rectisol process with methanol could do all these things in one single module. Although the objectives of the purification sections of Sasol I and II are the same, differences in the processing schemes do exist. For example, Sasol II will recover ammonia as anhydrous ammonia while Sasol I reacts ammonia vapors with sulfuric acid to produce ammonium sulfate. Also, Sasol II will make more use of air cooling.

The purified gas from the Rectisol process, containing less than 0.07 ppm sulfur, is sent to the Fischer-Tropsch synthesis. Sasol I has two types of synthesis: a fixed bed system which produces a high percent of heavier paraffin hydrocarbons for which a low volume market exists and a fluid bed system which produces more olefins and lighter hydrocarbons in the gasoline and diesel range. The fixed bed reactors have the draw-back that their possibilities for scale up are limited and their total capacity is small. At Sasol I, a reactor containing 2,000 tubes has a capacity of approximately 18,000 tons (16,000 mt) of product per year. Sasol II will produce 1.7 million tons (1.5 million mt) per year. The fluid bed reactor does not have such size limitations and can be confidently scaled up using well known technology. Since the objective of Sasol II is to produce motor fuel, only fluid bed reactors will be installed. Sasol II will contain seven fluid bed reactors. More motor fuel per ton (0.9 mt) of coal will be produced by Sasol II (1.78 barrels) than by Sasol I (1.26 barrels) since a smaller amount of other products (waxes, heavy hydrocarbons) will be produced at Sasol II.

The synthesis flow scheme for Sasol II is similar to that for the fluid bed reactors in Sasol I with the sequence of operations the same but the

details of auxiliary processes different. In addition, product recovery and refining are markedly different from Sasol I. In designing these operations, advantage has been taken of the experience gained at Sasol I and the most modern techniques of gaseous and liquid hydrocarbon processing.

At Sasol I, after cooling of the product gas, most of the non-condensed hydrocarbon products are recovered in an oil-wash system and the tail gas is used for pipeline gas or reformed back to hydrogen and carbon monoxide. Recovery of ethylene is low with most remaining in the tail gas. A low temperature Rectisol wash is used to remove carbon dioxide from the recycled synthesis tail gas. In the Sasol II plant, a more efficient hot potassium carbonate absorption will be used for removal of carbon dioxide. Also, the oil-wash system will be replaced by a low temperature unit which recovers as separate streams a light oil, a propane/butane stream, an ethane/ethylene stream, a stream of approximately 90% methane and a hydrogen rich stream. The ethane/ethylene fraction goes to an ethylene plant where the ethylene is recovered and the ethane recycled and cracked producing additional ethylene. The hydrogen rich stream is recycled to the Synthol reactors or is used for refinery operations. Part of the methane is used as internal fuel gas for the plant complex but the major portion is reformed by partial oxidation to hydrogen and carbon monoxide for recycle.

The product refinery is geared to the South African market which requires mainly motor fuels, the majority in the gasoline range. The light olefins are combined by polymerization and the polymer product will be partly hydrogenated to limit the final olefin content in the gasoline. The above 400°F (200°C) material will be cracked to produce diesel oil and some gasoline fractions. The gasoline components will be blended to regular and premium gasoline. Sasol II will produce the equivalent of a 40,000 barrel per day crude oil refinery.

Sasol II will be situated upstream of the large populated Witwatersrand area. The plant is being designed for maximum re-use of water within the plant and zero discharge to local drainage systems. The two main

sources of effluent are gasification which produces an aqueous liquor and Fischer-Tropsch synthesis which produces a watery effluent containing soluble oxygenates and organic acids. The aqueous liquor is first treated in a Phenosolvan plant where by extraction with isopropylether the water soluble phenols are recovered as a crude tar acid fraction and ammonia is stripped off the liquor and further purified by absorption. The Fischer-Tropsch reaction water is stripped of its non-acid chemicals which are recovered as marketable products such as ethanol, propanol, and acetone. The remaining effluent, containing organic acids, and the stripped aqueous liquor are then biologically treated in activated sludge units and further purified by ion exchangers and activated carbon to a purity where they can be used as cooling water make up. A purge stream from the cooling water system is used for hydraulic ash transport to the ash dewatering unit. The ash dewatering unit is an evaporative system involving a lined slimes dam and an ash dump. Total water input to the plant to replace losses and evaporation is in the range of 14,000 to 15,000 gallons per minute (3200 to 3400 m^3/h). Gaseous effluents must conform to South African codes. Power plant stacks will be about 500 feet (150 m) high for dispersion of boiler flue gas and Stretford process emission.

Sasol II is scheduled for completion early in 1980. As soon as Sasol II is finished construction will start nearby on Sasol III. The decision to build Sasol II was made in 1979 after the new government in Iran decided to cut off oil supplies to South Africa. Iran had been South Africa's principle supplier. In order to save time and design costs, Sasol III will be almost an exact copy of Sasol II and will cost $3.8 billion. Once the three plants are in operation, they will produce about 112,000 barrels of oil per day, approximately half of South Africa's needs in the 1980's. The three Sasol plants will decrease South Africa's dependence on imported oil; they will strengthen the base of the South African motor fuels and chemical industry; they will make a significant contribution to the saving of foreign exchange; they will provide a large number of job opportunities not only in the plants themselves but also in all the supporting services and industries for all groups of the South African community; and they will set a new standard in general for the coal conversion industry which can be considered as a target for second generation processes to improve upon.

5. Conclusions

The economic conditions for an oil-from-coal plant differ from country to country especially since the viability and degree of risk depend so much on non-technical factors such as government policy toward such a venture. The making of synthetic oil from coal works in South Africa because of a unique combination of factors including the availability of vast reserves of low cost coal, the scarcity of domestic petroleum resources, and the abundance of cheap labor. South Africa has coal reserves of 25 billion tons (23 billion mt). Almost 80% of South Africa's energy needs are met by utilizing coal. South Africa is boycotted by most of OPEC and is without oil reserves of its own. Therefore, South Africa has utilized technologies invented in Europe and the United States to convert its abundant coal resources to the forms of fuels and petrochemicals required by a highly technical society.

The United States has seven times the coal reserves of South Africa and a diminishing supply of domestic petroleum resources. Recent developments in the worldwide energy situation, especially the systematic OPEC price increases, have caused many Americans to express interest in Sasol-type coal-to-oil projects. There are, however, doubts about the economic feasibility of a Sasol-like plant for the United States. Comparisons are difficult because of the number of factors involved including the cost of coal, construction, and labor. It has been estimated that oil could not be produced from coal in the United States for less than $27 per barrel and perhaps as much as $45, compared with around $20 per barrel currently charged by OPEC. In addition, there are doubts about the complexity and high capital costs involved in scaling up such a process to meet American needs. South Africa is currently spending between six and seven billion dollars to increase its synthetic oil production to 112,000 barrels per day. This would be a drop in the oil bucket in the United States which uses 17.6 million barrels per day. Considering South Africa's gross national product and energy consumption, its effort is comparable to a $300 billion crash program for the United States.

Sasol's success indicates that producing synthetic fuels from coal can be technically and economically feasible. The technology is available and the Sasol process - coal gasification plus Fischer-Tropsch synthesis - is the only commercially proven process that will produce synthetic fuels quickly, on schedule, and at predictable costs.

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